VOLUME 77 SEPARATE No. 55

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

JANUARY, 1951

MEASUREMENT OF SEDIMENTATION IN SMALL RESERVOIRS

By L. C. Gottschalk

HYDRAULICS DIVISION

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

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Proceedings—Vol. 77 January, 1951 Separate No. 55

AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

PAPERS

MEASUREMENT OF SEDIMENTATION IN SMALL RESERVOIRS

By L. C. Gottschalk [1]

Synopsis

Measurements of the volume of sediment in reservoirs provide a basis for determining the extent of sedimentation damages, for periodically correcting the capacity curve to assure more efficient operation, for evaluating the effects of watershed and climatic factors on rates of sediment production from watersheds, and for developing sediment production indexes useful in the design of reservoirs. Sediment volumes may be determined by comparison of original contour maps with maps showing the present topography of the sediment surface or by direct measurement of sediment thicknesses. Two methods of survey are used by the Soil Conservation Service (SCS), United States Department of Agriculture—the contour method and the range method. Water depths are measured by use of a lead line, sounding pole, or echo sounder. Sediment thicknesses are determined by use of a spud, sounding pole, or soil auger. The specific weight of sediment (and watershed studies) is determined, and watershed studies are made in conjunction with reservoir sedimentation surveys. Water capacities and sediment volumes are computed for contour surveys by a modified prismoidal formula and for range surveys by the Dobson prismoidal formula.

Introduction

The need for sedimentation data in the design of water control and utilization projects has been so prominently emphasized in the past few years that it needs no further discussion in this paper. Slowly, but surely, much needed data are accumulating on rates of sediment production from drainage basins. The time has come when the emphasis should not be on why surveys should

Note.—Written comments are invited for publication; the last discussion should be submitted by July 1, 1951.

[1] Head, Sedimentation Section, Soil Conservation Service, U. S. Dept. of Agriculture, Washington, D. C.

be made but on how and where such surveys are to be made. Several scientific organizations have established committees to study the problem of reservoir sedimentation and to prepare recommendations on survey methods and techniques. The ASCE Joint Committee on Sedimentation in Reservoirs is an example. In general, there is a need for standardizing methods of making reservoir sedimentation surveys so that the results obtained by various federal and state agencies are comparable and useful to all. The methods described in this paper are those developed and used by the SCS for surveying small reservoirs.

In general, the purpose of a reservoir sedimentation survey is to measure the accumulated volume of sediment in a reservoir during the period of storage record. This information is useful for:

1. Determining the prevailing and probable future sedimentation damages to a particular reservoir;
2. Periodically correcting the capacity curve to assure more efficient operation;
3. In combination with similar data from other reservoirs and suspended load measurements, evaluating the effects of watershed and climatic factors on the rate of sedimentation; and
4. Preparing regional sediment production indexes for developing design data.

The procedures for measuring the accumulated volume of sediment in a reservoir, established by the SCS in 1934, in connection with a nationwide study of reservoir sedimentation, with minor variations, are rather widely used today (1950). These procedures have been adopted by various other federal and state agencies engaged in reservoir sedimentation studies. Therefore, a discussion of the methods developed by the SCS, to a large extent, covers the methods generally used throughout the United States, with the exception of special equipment such as echo sounders. The latter are of recent development and have been adopted as standard equipment by other federal agencies, particularly in surveying major reservoirs.

Equipment for Measuring Water Depths and Silt Thicknesses

General.—The volume of sediment in a reservoir may be determined by one of two methods:

a. By determining the present capacity and assuming that the difference between it and the original capacity is a measure of the volume of sediment; and
b. By direct measurement of the volume of sediment deposits.

The first method is satisfactory only where an accurate map of the original reservoir basin was made at or before closing of the dam. Such maps are usually few and far between, particularly on smaller and older reservoirs. On the newer major reservoirs, where modern methods of mapping have been used, such as multiplex, more accurate maps are available and the original capacity data are reliable enough for estimating sediment volume from the measured present capacity. It must be emphasized that any error in the

original capacity of the reservoir imparts an equal error in the computed volume of sediment. Although the difference between the estimated original capacity and the true original capacity may be small in terms of the total capacity, it may represent a sizable error in the estimated volume of sediment in a reservoir if the sediment volume is small in comparison with the total original capacity.

Sounding.—No matter what method is used for measuring the sediment volume in a reservoir, the present capacity must be determined. This is done by measuring the present water depths at representative points in the reservoir and computing the volume in respect to the surface area. Water depths may be measured by lead-line sounding, by use of a sounding pole, or by echo sounding. Only lead-line sounding and a sounding pole are used by the SCS for surveying small reservoirs. Both wire and rope sounding lines are used. Wire lines are wound on manually-operated reels with registering sheaves to

FIG. 1.—SOUNDING LINE BEING CAST WITH BOAT IN MOTION

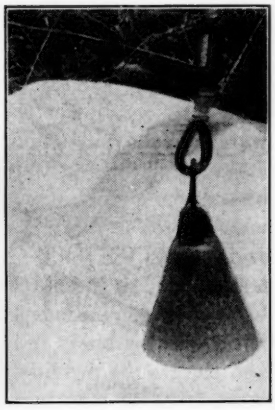

FIG. 2.—SOUNDING WEIGHT

measure the length of line "paid out." Depths can be determined accurately to 0.1 ft by reading a counter on the apparatus, but the boat must be stopped to obtain each depth reading. Rope sounding lines have been found more convenient to use than wire lines, mainly because soundings can be taken faster and because the SCS does not have boats of its own on which sounding reels can be mounted permanently. The SCS has found cotton-covered, bronze core tiller rope, $\frac{1}{4}$ in. in diameter, to be the most satisfactory for sounding lines because of the durability and the capability of such lines to maintain a constant length. Rope sounding lines are marked at 0.5-ft intervals, using a convenient color system of markings for identifying the 0.5-ft, 1.0-ft, and 5.0-ft marks, and different 10-ft intervals up to 150 ft. Water depths are measured accurately to 0.5 ft and estimated to the nearest 0.1 ft. In hand-line sounding, observations can be made for depths up to about 75 ft without stopping the boat (see Fig. 1). The sounding weight is cast ahead of the boat and allowed to sink to the bottom. The depth reading is taken when the boat is directly over the

sounding weight and the line is vertical. A bell-shaped cast aluminum sounding weight (see Fig. 2) is used for both wire-line sounding and hand-line sounding. A 5-lb all-aluminum weight is used for depths to 100 ft and a 9-lb weight equal in size to the 5-lb weight, but filled with lead, is used for greater depths. A bell-shaped weight permits rapid descent through the water and the wide, flat bottom prevents the weight from sinking too deeply into soft sediment deposits.

The sounding pole is a convenient tool for measuring shallow depths in small reservoirs and has been used with considerable success in determining sediment thicknesses as well. The use of a sounding pole is limited to depths not exceeding 30 ft. An ordinary 1½-in.-diameter closet rod, obtainable in most any lumber yard, has been found to be satisfactory. A closet rod may be obtained in 20-ft lengths or, more conveniently from the standpoint of transportability, in 10-ft lengths that can be spliced together. Recently the SCS has developed a lightweight steel sounding pole constructed from 1-in., thin-wall electrical conduit. It is made up in 5-ft sections which are fastened together by threaded dowels. It may be assembled to any length but sounding poles longer than 30 ft are too cumbersome to handle from small boats. Sounding poles are marked in color using the same system of marking as that on the hand line.

Echo sounding is the most practical and economical method of measuring water depths, particularly on large bodies of water where it is not necessary to make direct sediment thickness measurements for the accurate determination of sediment volumes. Echo sounding equipment consists of a transmitter which sends supersonic sound waves to the bottom and a receiver which receives and records the echo. The elapsed time for the sound wave to travel from the transmitter to the bottom and return to the receiver is a measure of the depth. Continuous soundings are made as the boat travels along the water. Sounding with echo sounders is faster and more accurate than sounding with lead line and the results provide a continuous profile of the bottom. A skilled operator is required to maintain and operate the equipment and its use requires boats larger than those ordinarily found on small reservoirs. Echo sounders are not economical to use for surveys which require direct sediment thickness measurements because the boat must be stopped for each measurement. Thus, ample time is available for measuring water depth with a lead line and the need for specialized equipment and personnel is eliminated. Since sediment thickness measurements are usually required on the smaller and older reservoirs surveyed by the SCS, this equipment is not used by this agency.

Sediment Thicknesses.—Where no maps or where maps of questionable accuracy are available on a reservoir, it is necessary to determine the volume of sediment in the reservoir by direct measurement of sediment thicknesses. This may be done with a spud, sounding pole, or auger. A spud is an instrument developed by the SCS specifically for this work. Several refinements have been made of this instrument since it was originally developed, the most recent being a sectional spud that can be packed in a carrying case for easy transportation. The spud (see Figs. 3 and 4) is a case-hardened or well-tempered steel rod, 1½ in. in diameter, into which encircling triangular grooves have been machined at intervals of 0.1 ft. Each groove tapers outward from

a maximum depth of $\frac{1}{4}$ in. to 0 at the rim of the groove 0.1 ft above. In appearance the spud resembles a series of inverted frustrums of cones with a maximum diameter of $1\frac{1}{2}$ in., a minimum diameter of 1 in., and an altitude of 0.1 ft, set vertically one on another. The base of each cone is machined to a depth of $\frac{1}{8}$ in. to form a cup in which to catch and hold the sediment. The spud is made up in 3-ft sections which can be assembled to any length up to 18 ft by nickel alloy steel dowel pins. The spud is attached to a $\frac{3}{8}$-in. or $\frac{1}{2}$-in (outside diameter) bronze core tiller rope and thrown downward from a boat with sufficient force to carry it through the sediment and into the original bottom materials of the reservoir. The spud is withdrawn from the original bottom materials and sediment by snubbing the line over the side of the boat and rocking the boat until the spud is jerked loose. The spud is pulled slowly through the water to the boat to prevent the sediment from washing off. The thickness of sediment is determined directly by inspection of the deposit and original bottom materials adhering to the spud. The spud has been used and found satisfactory for determining sediment thicknesses, in water depths up to several hundred feet.

FIG. 3.—SECTIONAL SPUD PACKED IN CARRYING CASE

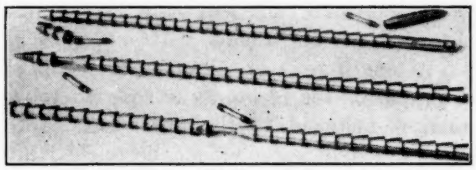

FIG. 4.—PARTLY ASSEMBLED SPUD

In shallow water, where depths to original reservoir bottom do not exceed 30 ft, a sounding pole has been found convenient for determining sediment thicknesses. Sediment often can be distinguished from original bottom materials by differences in compaction alone, even after sediment has been subjected to extended periods of aeration. The use of a sounding pole depends on this criterion for distinguishing the difference between original soil and sediment. The depth of water to the top of the sediment is measured by the sounding pole. The pole is then pushed through the sediment to the more resistant original bottom. The depth is again noted and the difference is a measure of the sediment thickness. The sounding pole is most useful for measuring sediment depths usually not exceeding 10 ft, particularly deposits having a high percentage of silt and clay fractions. The latter deposits usually are less compact than the bottom materials below.

Often the difference between sediment and bottom materials cannot be detected by difference in compaction alone. Then the thickness of sediment must be determined by inspection. In submerged deposits this can be done by the use of a spud if the deposits are not too compact and do not exceed 18 ft in thickness. If the deposits are too thick or too compact for measurement with a spud, a soil auger is used, consisting of a $1\frac{1}{2}$-in. bit fastened to a $1\frac{1}{2}$-in. (outside diameter) pipe. It is provided with 5-ft extensions so that it can

be assembled to any desired length. Deposits of as deep as 40 ft have been measured by use of this auger. The soil auger is particularly useful in measuring the thickness of exposed deposits such as may be found in the delta areas of reservoirs.

Under particularly favorable conditions, sound waves from echo sounders sometimes penetrate soft sediment to be reflected from a hard bottom as well as from the surface of the soft sediment. Under these conditions sediment thicknesses can be determined from the fathograms of echo sounders. Fathograms of Chesapeake Bay often show from 15 ft to 20 ft of soft sediment deposited in dredged navigation channels. Although this appears to be the exception rather than the rule, it does indicate the possibility that echo sounders could be developed which would record sediment thicknesses as well as water depths. Such instruments would probably require the use of sonic frequencies rather than the supersonic frequencies used in present day echo sounders because sonic frequencies have higher penetrating power and lower absorption than supersonic frequencies.

Specific Weight of Sediment.—A core type sampler has been developed by the SCS to obtain undisturbed samples of sediment for determining specific weight. It consists of a 4-ft length of 2-in. (outside diameter) galvanized iron pipe threaded at both ends. Attached to the upper end by a reducer is a 4.5-ft length of 1-in. pipe, on the end of which is a tee joint suitable for a handle or for fastening a rope to the sampler. A sampling nipple, 4 in. long, is fastened to the lower end of the 2-in. pipe by a coupling. The specific weight sampler can be pushed into the sediment by hand or can be thrown or withdrawn in the same manner as the spud. A flap valve, contained in the reducer, opens to permit the outflow of air and water as the specific weight sampler descends. When the sampler is withdrawn, the valve closes, creating a suction which holds the sediment in the sampler. The nipple is removed from the sampler, capped at both ends, and sent to the laboratory for specific weight analysis.

The Field Survey

Survey Methods.—Two general methods of determining the capacity of a reservoir are in use today—the contour method and the range method. The contour method requires an accurate original contour map of the reservoir basin, and both the range method and contour method require an accurate shore line map. If no maps, or if maps of questionable accuracy, exist on a reservoir, a shore line map is made by standard surveying methods. This consists of establishing primary control by a triangulation system extended upstream from a base line near, or on, the dam. If there are existing maps, and if they check well with this primary system, the maps may be used for the survey with minor corrections for the shore line contour if necessary. If no maps are available, or if existing maps are not good, and if no aerial photographs are available, the shore line is mapped with plane table and telescopic alidade.

Range ends, instrument stations, and triangulation stations are permanently monumented, using iron pipe set in concrete or reinforced precast concrete posts

with bronze caps. Station numbers are marked directly on the pipe or on the bronze caps with steel dies. Various scales are used for mapping, depending on the size of the reservoir. For small reservoirs and ponds a scale of 100 ft equal to 1 in. is used, whereas a scale of 1,000 ft equal to 1 in. is used for major reservoirs.

Shore line mapping is a time consuming job in the field. Its primary purpose is to locate survey stations for future reference and to determine the surface area needed to compute water and sediment volumes. The SCS has found it convenient to use aerial photographs for this purpose whenever possible. These may be "blown up" to any convenient scale, the scale depending on the size of reservoir surveyed. On larger reservoirs 500 ft equal to 1 in. is used and on smaller reservoirs 200 ft equal to 1 in. Because of inaccuracies on the outside borders of aerial photographs caused by parallax, only the center areas of the photographs are used. These are blown up to the desired scale, cut to plane-table size, and used on the plane table in the same manner as a regular plane-table sheet. If the water surface level of the reservoir was at crest elevation on the day the photograph was made, the shore line can be determined directly from the photograph. If not, the shore line contour must be determined by multiplex methods. In all cases the scale of each photograph is checked in the field by chaining the distance between two identifiable objects on the photographs.

Contour Survey.—Of the two methods of survey, the contour method gives more reliable results, provides a better picture of the vertical and horizontal distribution of sediment, and allows plotting of capacity curves. However, it requires more widely distributed observations than the range method and generally necessitates a longer period of survey. The contour method of survey consists of establishing elevations of the present sediment surface and sketching in the contours. The area enclosed by each contour is planimetered and the volume increment computed on the basis of the contour interval. The contour method is used by the SCS only for surveys of reservoirs which have original contour maps with a high standard of accuracy, where sediment cannot be penetrated by ordinary methods, and where sediment thicknesses are large enough to eliminate the possibility of sizable errors due to inaccuracies in original maps. In a contour survey an adequate number of accurately located soundings must be taken to afford a sure basis of interpolating contours on an invisible surface (the more irregular the surface, the more soundings required). Conversely, the more gentle and regular is the slope, the fewer are the soundings required. Several methods of locating observations may be used depending on the discretion of the instrumentman. Thus, in shallow water the direction and distance to an observation may be determined from a single instrument station using a transit or properly orientated plane table and stadia board. In deeper water, locations may be determined by plotting on the plane-table sheet the point of intersection of two direction lines from adjacent stations. Several patterns of soundings have been used, including radial, grid, and closely spaced ranges.

Range Survey.—The range method of survey is used more often than the contour method of survey by the SCS because much of its work is on small and older reservoirs where good original maps are not available. A range survey

can be made with much less field time than a contour survey. In a range survey, sediment thicknesses are measured directly. The range method consists of laying out a system of representative ranges (see Fig. 5) and determining the present water and sediment depths at regular intervals along these ranges. The boat is directed along this range and kept on line by a transit and a signalman on one end of the range or, if the range is short, by use of a backsight flag behind one of the range ends. The plane table is set up at a cut-in station, and the location of the soundings is predetermined and indicated lightly in pencil on the plane-table sheet. As the boat travels along the range, the instrumentman signals the boat crew when the boat is over the point where an observation is made. Simultaneous soundings and sediment-thickness measurements are made along the ranges at regularly spaced intervals of 25 ft to 50 ft on small reservoirs and 75 ft to 100 ft on large reservoirs. These are plotted on cross-sectional paper and the volume is computed on the basis of the segment areas between the ranges. The accuracy of this method depends on the variability of the topography of the reservoir and the proper selection of ranges to sample this variability adequately. Where the cross sections represent a good sampling of topography of the reservoir basin, a high degree of accuracy is attained. Results of surveys of reservoirs with regular shape are usually within 2% of the true value, whereas reservoirs of irregular shapes, with many embayments, variable valley characteristics, and long, winding arms, give results well within 10%.

Computation of Water Capacity and Sediment Volume

Contour Method of Survey.—For computing the sediment volume when the contour method of survey is used, water depths are plotted on the reservoir map and the present contours of the reservoir basin are drawn in. The area enclosed by each contour of original capacity and sediment deposits is then determined in acres from the reservoir map by planimeter. The original capacity and sediment volume are computed by the following modified prismoidal formula:

$$V = \frac{L}{3}(A_l + \sqrt{A_l A_u} + A_u) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which:

V = the capacity, in acre-feet;

L = the contour interval, in feet (in the lowest prismoid, L, is the vertical distance between the lowest contour and the lowest point in the bottom of the reservoir);

A_l = the area, in acres, of the original lower contour for original capacity, or the difference between the areas of the original lower contour and the present lower contour for sediment volume (in the lowest prismoid, $A_l = 0$, for both original capacity and sediment volume); and

A_u = the area, in acres, of the original upper contour for original capacity, or difference between the areas of the original upper contour and the present upper contour for sediment volume (in the uppermost prismoid, A_u is equal to the area enclosed by the crest contour).

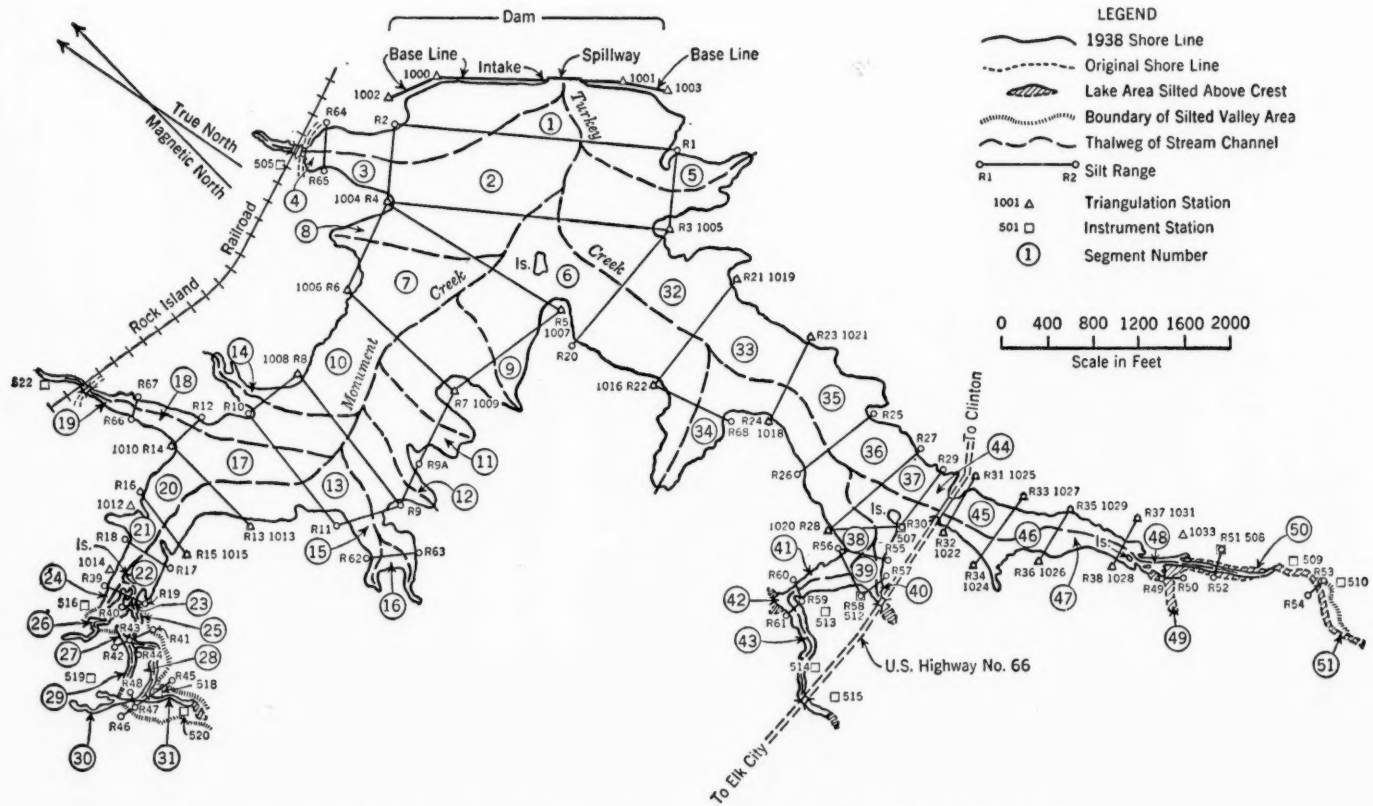

FIG. 5.—A MAP OF LAKE CLINTON, WASHITA COUNTY, OKLAHOMA, SHOWING TYPICAL RANGE LAYOUT

Range Method of Survey.—In the range method of survey, ranges are laid out parallel to each other, as far as possible. The measured water depth and sediment thicknesses along these ranges are plotted on cross-section paper and the cross-sectional areas of original capacity and silt volume are determined in square feet, by planimeter (see Fig. 6). The segment areas, or those areas

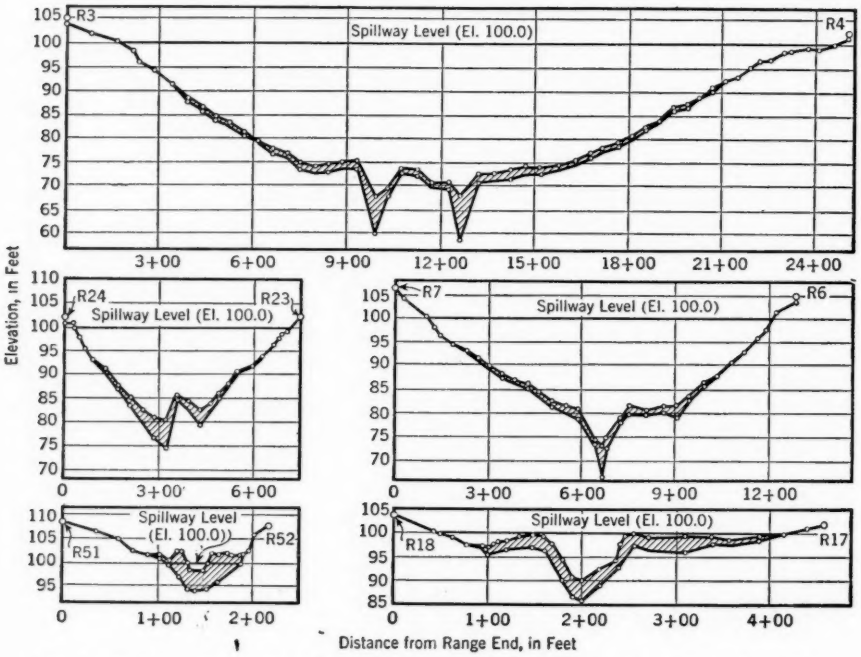

FIG. 6.—REPRESENTATIVE CROSS SECTIONS OF LAKE CLINTON, WASHITA COUNTY, OKLAHOMA

bounded by a set of ranges and crest-line contour, are determined in acres from a map or aerial photograph of the lake, using a planimeter. The volume of water or sediment in each segment is determined by the Dobson prismoidal formula:[2]

$$V_s = \frac{A'}{3}\left(\frac{E_1 + E_2}{W_1 + W_2}\right) + \frac{A}{3}\left(\frac{E_1}{W_1} + \frac{E_2}{W_2}\right) + \frac{h_3 E_3 + h_4 E_4}{130{,}680} + \cdots \quad ..(2)$$

in which:

V_s = the original capacity or sediment volume, in acre-feet;
A' = the quadrilateral area formed on two sides by the range ends and on the other two sides by lines drawn from the intersection of the range lines and crest contour, in acres;
A = the segment area of the reservoir, in acres;
E = the cross-sectional area of water or sediment along the range, in square feet;

[2] "Silting of Reservoirs," by Henry M. Eakin, *Technical Bulletin No. 524*, U.S.D.A., revised by Carl B. Brown, U. S. Government Printing Office, Washington, D. C., 1939.

W = the width (length of bounding range) at crest elevation, in feet; and
h = the perpendicular distance from the range on a tributary to the junction of the tributary to the main stream; or, if this junction is outside the segment, to the point where the thalweg of the tributary intersects the downstream range.

Eq. 2 applies to segments with irregular shore line and is applicable only for ranges that are essentially parallel. In curved segments with regular shore line, the following average end-area formula gives more reliable results:

$$V = \frac{A}{2}\left(\frac{E_1}{W_1} + \frac{E_2}{W_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The volumes of water and sediment are computed separately for each segment of the reservoir, with proper correction for the water and sediment displacement by the dam in the segment immediately upstream from the dam, and the individual segment volumes are totaled to obtain the entire water and sediment volume in the reservoir.

Presentation of Data.—It has been a set policy of the SCS to prepare reports on all detailed sedimentation surveys so that the data can be made available to all who have use for them. One comprehensive printed report[2] was issued in 1936 (revised in 1939) which includes information on all the detailed reservoir sedimentation surveys made by the SCS to that date. Numerous reports have been prepared on surveys of individual reservoirs in mimeographed or multilithed form. These reports give detailed information on the dam and the reservoir, methods of survey, sediment characteristics, and watershed characteristics, as well as a summary of sedimentation data in terms of storage loss and rate of sediment production per unit of drainage area on both a volumetric basis and a weight basis.

Summary

The methods developed by the SCS to determine the volume of sediment in reservoirs give results which are well within 10% of the true values. The results, therefore, are reliable for estimating sediment damages to individual reservoirs, for correcting capacity curves, for evaluating the effects of watershed and climatic factors on sedimentation, and for developing sediment production indexes for specific problem areas. The methods described have been adopted to a large degree by the various federal, state, and local agencies engaged in reservoir sedimentation investigations. The results of such investigations, therefore, are comparable in accuracy and are useful to all concerned with the problem of reservoir sedimentation.

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